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Evaluation of Minimally-Intrusive Power Generation Alternatives for a Nuclear Thermal Propulsion Engine

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Abstract

There are two design ideas in consideration for the Nuclear Thermal Propulsion reactor. One in which the reactor cannot be turned all the way off or else the fuel elements will cool past their ductile-to-brittle transition temperature. Past this temperature, the fuel elements face embrittlement issues. For this design, after the reactor is used at full power to provide thrust for a burn, the power level will be lowered to an idle mode in order to keep the fuel elements above their ductile-to-brittle transition temperature (DBTT). At this lower power level, the reactor will be generating about 15 Megawatts-thermal (MWt). The other design idea allows the reactor to be turned all the way off between burns, since embrittlement is not a concern with this design. This paper discusses the use of a Minimally-Intrusive Power generation System (MIPS) for both design scenarios. For the design in which the reactor power will be reduced to 15 MWt, a MIPS can remove some of the heat generated by the rector in idle mode and removed by the non-propulsive hydrogen coolant loop and convert it to usable power for the vehicle without any changes to the reactor design and only minimal changes to the engine design. For the design in which the reactor can be turned all the way off, the reactor power will be reduced to just enough power to operate the MIPS, no more. The specific application for this MIPS study is for a crewed Mars Transfer Vehicle (MTV) for a round-trip mission to Mars. The power conversion systems considered in this study are a closed-loop Brayton cycle, a Stirling engine, and thermoelectric generators (TEGs). The masses of these systems were compared to the current system for power generation for the MTV – solar arrays. It was determined that for the design in which the reactor cannot be turned all the way off, the Stirling engines and Brayton engines resulted in lower masses when compared to the solar arrays. It was determined that for the design in which the engine can be turned all the way off, the Brayton engine was least massive for power levels above about 30 kWe, and the solar arrays were least massive for power levels below 30 kWe.

Keywords: Nuclear Thermal Propulsion, Power Generation, Stirling, Brayton, Thermoelectric Generators

Nomenclature

A_s = surface area
α = absorptivity
C_p = constant pressure specific heat of working fluid
C_V = constant volume specific heat of working fluid
ε = emissivity
G = generator efficiency
G_s = solar flux
h = specific enthalpy of working fluid
m = mass of working fluid
$\dot{m}$ = mass flow rate of working fluid
P = power
p = pressure
PR = pressure ratio
$\dot{Q}_{in}$ = heat flow rate in
R = gas constant
s = entropy
T = temperature
U = molar specific internal energy
θ = sun incident angle
V = volume
$\dot{W}$ = work flow rate
η = efficiency

Acronyms/Abbreviations

Ductile-to-Brittle Transition Temperature (DBTT)
General-Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG)
Idle Mode Radiator (IMR)
Kilowatt-Electric (kWe)
Kilowatt-Thermal (kWt)
Minimally-Intrusive Power generation System (MIPS)
Mars Transfer Vehicle (MTV)
Megawatt-Thermal (MWt)
Nuclear Thermal Propulsion (NTP)
Silicon Germanium (SiGe)
Space Power Demonstrator Engine (SPDE)
Space Power Research Engine (SPRE)
Technology Demonstrator Converter (TDC)

Thermoelectric Generator (TEG)

1. Introduction

The Nuclear Thermal Propulsion (NTP) Project was established in 2015 as a part of NASA's Space Technology Mission Directorate with the intention to "determine the feasibility and affordability of a low-enriched uranium-based Nuclear Thermal Propulsion engine with solid cost and schedule confidence" [1]. NTP offers very high energy density and specific impulse roughly double that of the highest performing traditional chemical propulsion systems. NTP may offer the only viable option for human exploration missions to Mars and beyond, where solar arrays can no longer provide sufficient energy and chemical propulsion would require prohibitively high masses of propellant and/or prolonged mission durations.

In most exploration mission scenarios, multiple burns of the propulsion system are needed at different points in the trajectory, primarily to exit or enter orbits of planets or moons. There are two design ideas being considered for the reactor. One in which the fuel elements are tungsten-cermet, and therefore, the reactor cannot be turned all the way off between burns or else the fuel elements will cool past their ductile-to-brittle transition temperature (DBTT). Past this temperature, the fuel elements will face embrittlement concerns. Therefore, for this design, the reactor power level will be reduced to an idle mode. While in this idle mode, the reactor will be generating about 15 MW of heat [2] which is low compared to the 540 MW it produces in full-power mode. This design will be referred to as Design A. Design A calls for a non-propulsive hydrogen coolant loop to cool the reactor while in its idle mode. For the other design idea, the reactor fuel elements are carbide-based. Therefore, embrittlement is not a concern, so the reactor can be turned all the way off between burns. This design will be referred to as Design B.

Bimodal Nuclear Thermal Propulsion involves running the reactor at a low power level in order to generate a given amount of electrical power to the vehicle. The ESCORT Bimodal design gained much attention in 2005 for its proposed capability to provide 50 kWe of power and its potential for substantial mass savings. In its power generating mode, the reactor is used to heat a helium/xenon working fluid to drive a closed-loop Brayton cycle. This closed loop Brayton cycle also serves to remove decay heat after the propulsion mode is over. However, interest in Bimodal NTP subsided because it calls for intrusive of changes to the reactor design, such as material changes, changes to the number of coolant channels, and changes to the length of the fuel rods [1], [3].

Thus, gave way to the idea of a Minimally-Intrusive Power generation System (MIPS). In the case of Design A, the MIPS aims to take some of the heat generated by the reactor in idle mode and convert it into usable power for the vehicle without any changes to the reactor design and only minimal changes to the non-propulsive hydrogen coolant loop for the engine. For the case of Design B, the MIPS design calls for the reactor to be operated at a very low power level – just enough to run the power conversion cycle, no more, also with no changes to the reactor design and only minimal changes to the engine design. The specific application for this MIPS study is also for a crewed Mars Transport Vehicle (MTV) for a round-trip mission to Mars.

Once the nuclear reactor has completed operating at full-power mode, it will continue to generate decay heat due to the continued radioactive decay of fission products in the core. Post-operational heat is a function of the power level at which the reactor operated before shutdown, and the length of time the reactor operated at that power level. This heat must be actively removed in order to prevent damage to the reactor [1]. The baseline approach for decay heat removal consists of hydrogen being pulsed through each core after each burn until the reactor reaches idle conditions for Design A, [1] or off for Design B.

For a nominal four burn mission, there will be three periods in which the reactor is not needed for propulsion. The first period will last 159 days between burns 1 and 2, the second will last 622 days between burns 2 and 3, and the third will last 159 days between burns 3 and 4 [1]. This totals to 940 days in which the reactor will not be needed for propulsion and the MIPS can be employed to provide power to the vehicle.

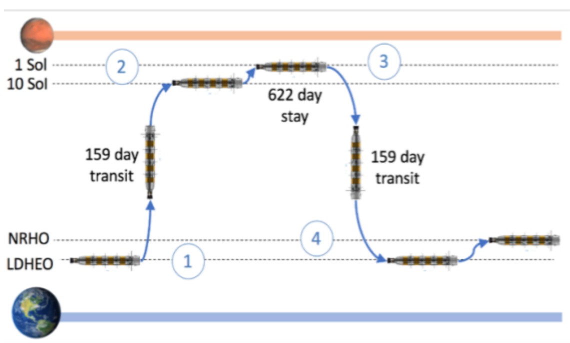

Fig. 1. Mars NTP Mission Bat Chart [1]

2. Material and Methods

For this study, it is assumed that the MTV requires between 25 kWe, twice that of the Orion module [4], to 100 kWe, about that of the International Space Station [5]. In the case of Design A, in order to achieve electricity for the vehicle, the heat from the non-propulsive hydrogen coolant loop must be converted through a power conversion cycle. In the case of Design B, the reactor must be operated at a very low power level and the engine design must be slightly altered in order to access this heat. The heat produced by the reactor in Design B must also be converted through a power conversion cycle in order to provide electricity to the vehicle. Alternatives for power conversion, for Design A and Design B, are: thermoelectric generators, a closed-loop Brayton cycle, and a Stirling cycle.

Thermoelectric generators (TEGs) convert thermal energy directly into electrical energy by exploiting a temperature gradient across a semiconductor to produce a voltage potential. TEGs were used on Voyager 1, Voyager 2, Cassini, and New Horizons spacecraft [6] because they are reliable in a deep-space environment. Alternatives two and three consists of dynamic power conversion systems: a closed-loop Brayton cycle and a Stirling engine. A closed-loop Brayton cycle was used to power the Near Infrared and Multi-Object Spectrometer aboard the Hubble Space Telescope from 2002 to 2008. The Brayton cycle was chosen because of its long-operational life and minimal vibrations [7]. Glenn Research Center successfully demonstrated the power capabilities of a Stirling converter with their Technology Demonstrator Converters (TDCs). TDC #13 holds the record for longest running heat engine as of 2018, fourteen years, and still shows no sign of wear.

Mass is always a consideration in spacecraft and space transportation vehicle design. In order to make the MIPS worthwhile, the mass of the system needs to be minimized. Specifically, it needs to be less massive than the solar arrays the vehicle would be forced to carry otherwise.

3. Theory and Calculation

The mathematical modeling for this study was done using MATLAB and Simulink, and the mass modeling was done using Creo Parametric. As stated previously, the MTV is assumed to require somewhere between 25 kWe and 100 kWe. Therefore, the mass and power level data were evaluated between 25 kWe and 100 kWe in increments of 25 kWe.

3.1 Thermoelectric Generators

The first power conversion system modeled was the TEGs. The power output for TEGs depends greatly on the material properties. The material to serve as the semiconductor for the TEG MIPS was chosen to be Silicon Germanium (SiGe). SiGe was used on radioisotope thermoelectric generators on Cassini and New Horizons [6]. The mathematical model for the TEGs is down below in equation (1).

$$P = \eta \dot{Q}_{in} \qquad (1)$$

The General Purpose Heat Source – Radioisotope Thermoelectric Generator has an efficiency of 6.3%, so the TEG MIPS efficiency was taken to be 6.3%.

The TEG architecture for this study was the same as the General-Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG) without the plutonium capsule and heat shield. Since the whole GPHS-RTG weighs 123.24 lbm, and the mass of the plutonium capsule and the heat shield is 56.75 lbm, the mass of the TEG equipment alone can be taken to be 66.29 lbm. Therefore, the mass of each TEG module is 66.49 pounds. Calculations were performed to determine how many TEG modules were needed to reach the given power level, and for how many modules were required, what that equated to in mass. The mass and power level data points were plotted on a mass vs power graph.

3.2 Brayton Cycle

The second alternative power generation cycle considered is the closed-loop Brayton cycle, shown in Figures 2 through 4.

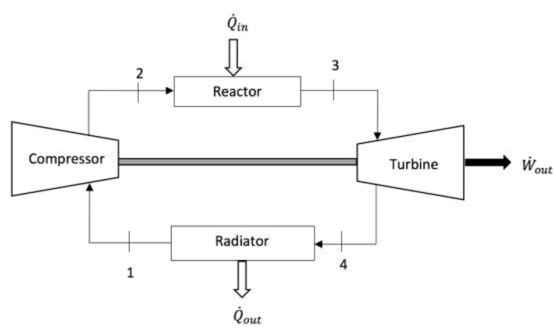

Fig. 2. Closed-loop Brayton Cycle Schematic [8]

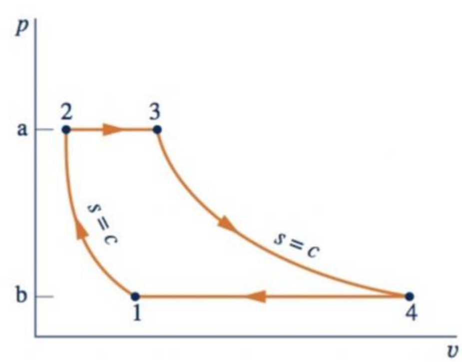

Fig. 3. Closed-loop Brayton Cycle Pressure vs Volume

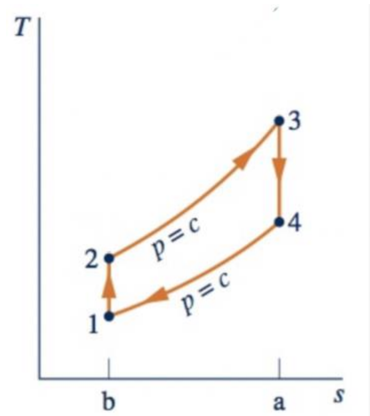

Fig. 4. Closed-loop Brayton Cycle Temperature vs Entropy

The mathematical model of the Brayton cycle was modeled in Simulink. Starting with the reactor, given the temperature of the working fluid leaving the reactor (T_3), the pressure of the working fluid entering the reactor (p_2), the pressure ratio of the reactor, ($PR_{reactor}$), and the power output desired (*Power*), one can get the pressure of the working fluid leaving the reactor (p_3) and the heat input required from the reactor ($\dot{Q}_{in}$), from the following equations.

$$p_3 = \frac{p_2}{PR_{reactor}} \tag{2}$$

$$\dot{Q}_{in} = \dot{m}(h_3 - h_2) \tag{3}$$

h_3 and h_2 come from a line of code that calls CoolProp in MATALB. For the turbine, the Simulink model requires a given efficiency of the turbine ($\eta_{turbine}$). Then, using equations (4) and (5), one can get the work done by the turbine.

$$h_4 = h_3 - (h_3 - h_{4s})\eta_{turbine} \tag{4}$$

$$W_{turbine} = \dot{m}(h_3 - h_4) \tag{5}$$

For the radiator, equation (6) gives the pressure of the working fluid leaving the radiator. Equation (7) gives the heat removed from the cycle by the radiator, and equation (8) gives the heat radiated out to space.

$$P_1 = P_4/PR_{radiator} \tag{6}$$

$$\dot{Q}_{out} = \dot{m}(h_4 - h_1) \tag{7}$$

$$\dot{Q}_{rad} = G_s \alpha \cos\theta + \frac{\dot{Q}_{out}}{A_S - \varepsilon\sigma(T_S^4 - T_\infty^4)} \tag{8}$$

For the compressor, the model needs to be provided with an assumed efficiency of the compressor ($\eta_{compressor}$). Then, using equations (9), (10), (11), and (12), the work available can be calculated.

$$h_2 = h_1 + (h_{2s} - h_1)/\eta_{compressor} \tag{9}$$

$$W_{required} = \dot{m}(h_2 - h_1) \tag{10}$$

$$W_{compressor} = W_{required}\eta_{compressor} \tag{11}$$

$$W_{available} = W_{turbine} - W_{compressor} \tag{12}$$

The Brayton cycle takes thermal heat and converts it into mechanical work. The alternator takes mechanical work and converts it into electrical power. This is how the MIPS will provide power to the vehicle. The equation for power from the alternator is given by equation (13) where the efficiency of the alternator is assumed.

$$Power = W_{Avaliable}\eta_{alternator} \tag{13}$$

The specific enthalpies were calculated using CoolProp in MATLAB. For the radiator, the surface area was assumed to be 190 m^2, that of the International Space Station. The surface area of the radiator was held constant between desired power output increments and the surface temperature of the radiator was varied to account for higher power levels. The working fluid of the system in this case is hydrogen. The efficiencies of the turbine and the compressor were both assumed to be 80% and the efficiency of the alternator was assumed to be 90% [9]. For the radiator calculations, T_∞ was taken to be 4 K [10], and G_s was taken to be 1367 W/m^2 [11]. It was assumed that the outer layer of the radiators was to be made of carbon-carbon composite. Therefore, α was taken to be 0.005 [12] and ε was taken to be 0.8 [13]. p_1 was taken to be 1 atm and p_2 was taken to be 13 atm, since a normal pressure ratio for a Brayton cycle is between 11 and 20 [8].

Creo Parametric was used to model the components of the Brayton engine to estimate the mass of the system. The 25 kWe Brayton engine was modeled using the dimensions and material specifications found in the *NASA Document for the Solar Dynamic Power System for Space Station Freedom* [14]. The Creo model of the 25 kWe engine turboalternator components was then scaled up by scaling factors that came from calculations and iterations to get the mass of the engine's turboalternator components to match that of the scaling curve given by historical data for each of the remaining power increments. The scaling curve for the Brayton engine turboalternator components is shown below in Figure 5. Figure 5 shows that the mass of the turboalternator components scale logarithmically. This is because the specific power of the turboalternator components scale with logarithmic decay [15], which is what makes the Brayton cycle so appealing for high-power level systems.

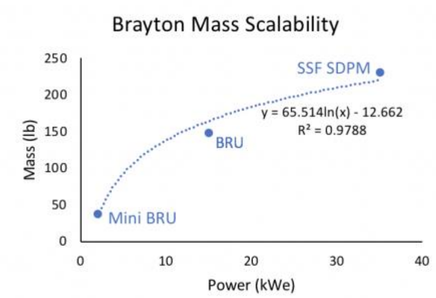

Fig. 5. Brayton Mass Scalability [15]

The Creo model was then scaled up to get the masses of the 50 kWe, 75 kWe, and 100 kWe Brayton engines. The data points in Figure 5 are for the Mini-Brayton Rotating Unit (Mini BRU), the Brayton Rotating Unit (BRU) and the Space Station Freedom Solar Dynamic Power Module (SSF SPDM) [15].

3.3 Stirling Cycle

The third alternative power generation for this study is the Stirling cycle. A schematic of the Stirling engine can be shown in Figure 6.

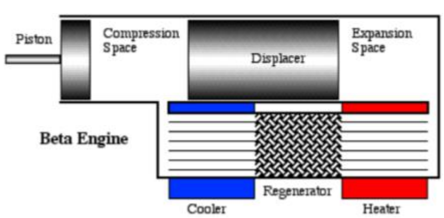

Fig. 6. Beta Stirling Engine Schematic

A pressure vs volume diagram is shown in Figure 7 and a temperature vs entropy diagram is shown in Figure 8.

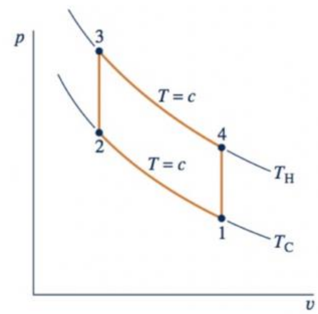

Fig. 7. Stirling Cycle Pressure vs Volume

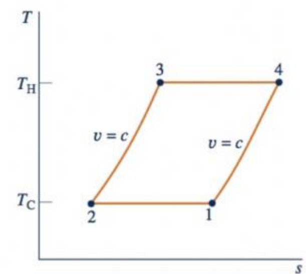

Fig. 8. Stirling Cycle Temperature vs Entropy

The compression ratio is given in Equation (14)

$$CR = \left(\frac{T_H}{T_C}\right)^{1/(1-\left(\frac{1}{\gamma}\right))} \tag{14}$$

The necessary mass of the working fluid is given by Equation (15).

$$m = \frac{\dot{Q}_{in}}{U_H - U_C + U_C \ln(CR)} \tag{15}$$

The efficiency of the cycle is given by Equation (16).

$$\eta_{Stirling} = \frac{mU_C \ln(CR)}{m(U_H - U_C) + mU_C \ln(CR)} \tag{16}$$

Finally, the power output is given by equation (17).

$$P = G\eta_{Stirling}\dot{Q}_{in} \tag{17}$$

The mass of the Stirling engine was determined first by modeling the engine dimensions and material specification shown in NASA's *SPDE/SPRE Final Summary Report* [9], a conference paper on NASA Lewis Stirling SPRE testing [16], and a contractor report for the SPDE [17]. The engine was then scaled up in Creo to get the masses of the 50 kWe, 75 kWe, and 100 kWe Stirling engines.

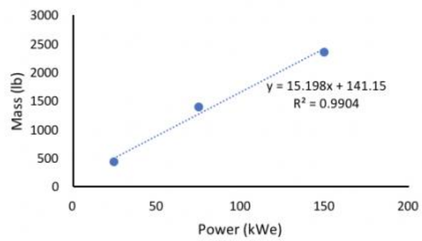

Fig. 9. Stirling Mass Scalability

The data points in Figure 9 came from the *Space Power Free-Piston Stirling Engine Scaling Study* [14]. For the 25 kWe engine, the engine had a specific mass of 8.23 kg/kWe, thus the engine mass was 207 kg (456 lbm). For the 75 kWe engine, the engine had a specific mass of 8.4 kg/kWe, thus the engine mass was 630 kg (1389 lbm). And, for the 150 kWe engine, the engine had a specific mass of 7.19 kg/kWe, thus the engine mass was 1078.5 kg (2377 lbm).

4. Results

For the case of Design A, where the reactor will be running at 15 MWt between burns, the following figure shows the mass vs power graph for each of the three MIPS alternatives investigated, alongside the mass of the solar arrays for each of the power levels considered.

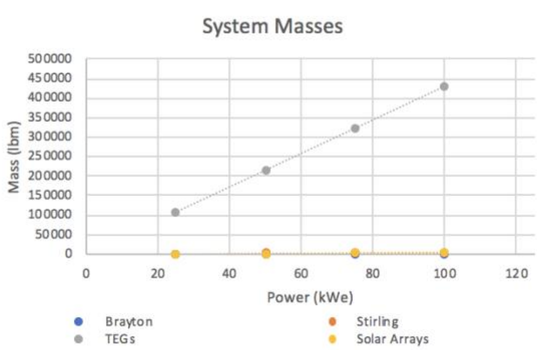

Figure 10. Design A System Masses vs Power

It can be seen from Figure 10 that the TEGs are the most massive. So massive, that they skew the graph and it is difficult to see how the other alternatives compare. Therefore, for Figure 11, the. TEGs have been left off the graph.

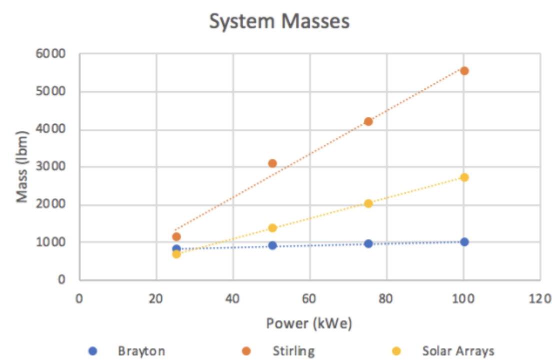

Figure 11. Design A System Masses vs Power without TEGs

It can. be seen here that the Stirling MIPS is the most massive, followed by the solar arrays and the Brayton. MIPS. However, for Design A, it is important to consider the fact that the heat coming from the reactor at idle that is not taken in by the MIPS still needs to be radiated out to space by the Idle Mode Radiators (IMRs). The reactor itself can handle 7 kWt [2], but all the idle heat remaining will be radiated out through the IMRs. In the case of the solar arrays, there is no MIPS to take in any of that idle heat, so all 14.993 MWt will need to be radiated out through the IMRs. In the case of the MIPS, the MIPS takes in some of the heat coming from the reactor at idle, so the IMRs will be smaller, since they will not need to radiate out as much heat. The relationship between mass of the power generation systems plus the mass of the IMRs vs power level are shown below in Figure 12.

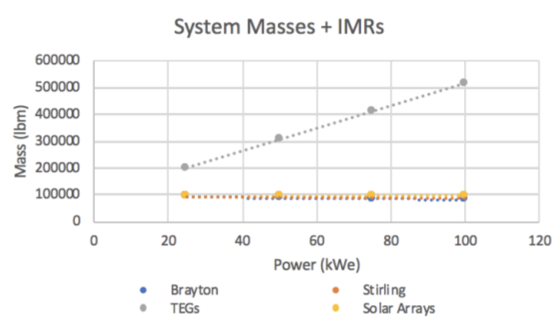

Figure 12. Design A System Masses plus IMRs vs Power

Once again, the TEGs are so massive, that it is difficult to see how the other alternatives compare. For that reason, the TEGs were left off the graph in Figure. 13.

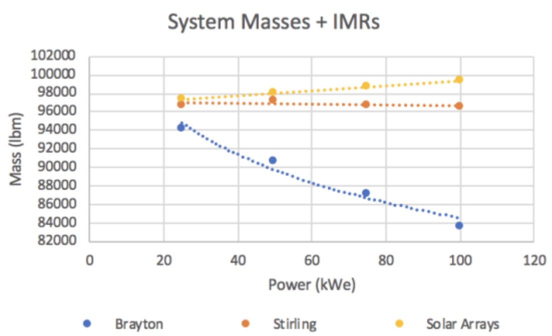

Figure 13. Design A System Masses + IMRs vs Power without TEGs

For the case of Design B, the reactor is operated at just enough power to run the MIPS, no more. Therefore, there is no need for IMRs. The following figure shows the mass vs power relationship of the MIPS alternatives alongside the solar arrays. Again, the TEGs were excluded from the graph because they were so massive.

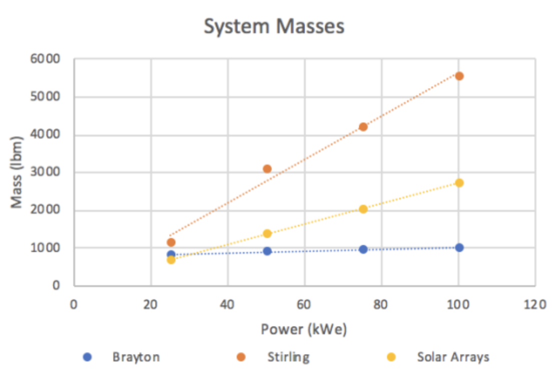

Figure 14. Design B System Masses vs Power

It can be seen that for the case of Design B, the TEGs are the most massive, followed by the Stirling engines. As for the Brayton engines and solar arrays, the solar arrays are less massive for power levels below about 30 kWe. The Brayton engines are less massive for power levels above about 30 kWe.

5. Discussion

For Design A, it can be seen in Figure 11, that in the case of the Brayton engine MIPS and the Stirling engine MIPS, the mass of the power generation system plus the IMRs actually decreases with power. This is because, as the power requirement increases, the MIPS must draw in more heat from the non-propulsive hydrogen coolant loop, and therefore less heat is left that needs to be radiated out through the IMRs, making them smaller and thus less massive. Since there is no MIPS to take in any of the idle heat in the case of the solar arrays, the IMRs must radiate out all 14.993 MWt coming from the reactor. The TEG MIPS also requires IMRs, but only for the remaining heat not taken in by the TEGs.

For Design B, there is no need for IMRs so the only factor to consider is the mass of the power generation systems themselves. Table 1, below, lists the preferred solutions for each of the desired power levels, for both Design A and Design B.

Table 1 – Preferred Solution

	Design A	**Design B**
25 kWe	Brayton MIPS	Solar Arrays
50 kWe	Brayton MIPS	Brayton MIPS
75 kWe	Brayton MIPS	Brayton MIPS
100 kWe	Brayton MIPS	Brayton MIPS

6. Conclusions

For the case of Design B, the Brayton engines are less massive than the solar arrays for power levels above about 30 kWe. Therefore, if decision makers decide on Design B, if the power requirement for the MTV ends up being above 30 kWe, it might be worthwhile to take a closer look at the Brayton engine as the power generation system. However, for the case of Design A, of the three MIPS alternatives considered, the Brayton engines and the Stirling engines result in mass savings for every power level considered between 25 kWe and 100 kWe when compared to the solar arrays the vehicle would be forced to carry otherwise. Therefore, if decision makers decide to go with Design A, the Brayton engines and the Stirling engines merit further investigation, such as sensitivity analysis, reliability analysis, and cost analysis. If decision makers decide to go with Design B, the Brayton cycle merits further investigation.

Acknowledgements

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References

[1] S. B. Rawlins and D. L. D. Thomas, “A Proposed Solution to Address Nuclear Thermal Propulsion Fuel Embrittlement and Cryogenic Hydrogen Requirements,” p. 5.

[2] Jennings, T., "DTM 2.0 Reactivity Closed Loop Control," Aerojet Rocketdyne, 2019

[3] S. Borowski and M. McGuire, “Vehicle and Mission Design Options for the Human Exploration of Mars/Phobos Using ‘Bimodal’

NTR and LANTR Propulsion," *NASA*, no. NASA/TM-1998-208834, Dec. 1998.

[4] National Aeronautics and Space Administration, "Orion" NP-2010-10-025-JSC

[5] M. Garcia, "International Space Station Solar Arrays," *NASA*, Jul. 31, 2017. http://www.nasa.gov/mission_pages/station/structure/elements/solar_arrays.html (accessed Jul. 27, 2020).

[6] F. Cheng, "Calculation Methods for Thermoelectric Generator Performance," *Thermoelectr. Power Gener. - Look Trends Technol.*, Dec. 2016, doi: 10.5772/65596.

[7] "Success Stories," *Creare*. https://www.creare.com/impact/success-stories/ (accessed Jul. 27, 2020).

[8] Moran, M. J., *Fundamentals of Engineering Thermodynamics: 8th Ed.*, Wiley, 2014

[9] Dochat, G., "SPDE/SPRE Final Summary Report," NASA Contractor Report 187086, p. 98.

[10] P. Ball, "Space: How cold does it get when we leave Earth?" https://www.bbc.com/future/article/20130920-how-cold-is-space-really (accessed Jun. 26, 2021).

[11] "Insolation - Energy Education." https://energyeducation.ca/encyclopedia/Insolation (accessed Jun. 26, 2021).

[12] Mills, A. F., and Coimbra, C. F. M., *Heat Transfer: Third Edition*, Temporal Publishing, LLC, 2016

[13] "Emissivity of High-Temperature Fiber Composites | Industrial & Engineering Chemistry Research." https://pubs.acs.org/doi/pdf/10.1021/ie8008583 (accessed Jun. 26, 2021).

[14] "Space Power Free-Piston Stirling Engine Scaling Study," NASA CR-182218

[15] L. Mason, R. Shaltens, J. Dolce, and R. Cataldo, "Status of Brayton cycle power conversion development at NASA GRC," vol. 608, Feb. 2002, doi: 10.1063/1.1449813.

[16] T. Brown, "Space Power Demonstrator Engine," p. 240.

[17] W. A. Wong, J. E. Cairelli, D. M. Swec, T. J. Doeberling, T. F. Lakatos, and F. J. Madi, "NASA Lewis Stirling SPRE Testing and Analysis with Reduced Number of Cooler Tubes," Aug. 1992, p. 929396. doi: 10.4271/929396.